Abstract—Steerable drills have the potential to minimize the required dimensions of incisions in minimally invasive spine fusion (MISF). Existing steerable drills mostly rely on flexible continuum mechanisms to create distal tip steerability. However, due to their inherent compliance and underactuation, high stiffness and dexterity cannot be achieved at the same time, which limits their application. In this paper, we present a 26.4-mm robotic steerable surgical drill offering high stiffness, strength, and dexterity, simultaneously. Contrary to existing flexible-transmission-based approaches, we use non-flexible transmissions (tendon-driven articulated joints and universal joints) to provide two distal degrees of freedom. To evaluate its performance, we integrated it with a customized tendon actuation platform for mechanical performance tests and the da Vinci Research Kit (dVRK), as an exchangeable instrument, for robotic steerable drilling tests. The results of these tests showed that our drill had high strength, stiffness, accuracy, and drilling stability while preserving high steerability and was sufficient to complete hole drilling in confined space in MISF.

I. INTRODUCTION

Spine fusion is a surgical technique used to fuse two or more vertebrae. It is commonly performed for treating various conditions of the spine, including deformity, trauma, degenerative disc disease, and spondylolisthesis [1]. In this procedure, surgeons generally replace entire intervertebral discs between vertebrae with cages and bone grafts and fix the vertebrae using screws, rods, plates, etc. [2]. In recent years, minimally invasive spine fusion (MISF) has gained increasing adoption due to less muscle damage and blood loss, which generally lead to less postoperative pain and shorter recovery time [3], [4].

Surgical drills are widely used for preparing screw holes in MISF. Due to the straight shafts of existing surgical drills, a large incision is generally created to allow a drill shaft to reach target drilling sites on vertebrae. With distal steerability, a surgical drill can potentially reach the target drilling sites through a smaller incision to minimize collateral tissue damage. As an example for illustration, for lumbar spine fusion, pedicle screws are generally placed on consecutive vertebrae, and a short rod is used to connect the screws, to prevent relative motion between the vertebrae [3]. As shown in Fig. 1, conventional straight-shaft drills require a large drill shaft span while a steerable drill can reach target sites with a smaller drill shaft span owing to the distal steerability.

Unlike existing dexterous surgical instruments designed for soft-tissue surgery, a surgical drill requires high stiffness and strength to deal with hard bony tissues. When drilling bony tissues, a drill is subjected to various disturbances, such as driving torques, axial thrust forces, shear forces, and bending moments [5]. Therefore, high stiffness is essential to maintain drilling stability and precision, especially in spine-related surgery, where target surgical sites are close to the spinal cord and nerves. Besides, high strength ensures a drill will not break under those disturbance forces.

Researchers have developed various robotic-assisted steerable drills to achieve higher dexterity in confined anatomical space for various surgical procedures, including anterior cruciate ligament (ACL) reconstruction [6], core decompression of femoral head osteonecrosis [7], pelvic osteolysis treatment [8], [9], and total hip arthroplasty [10]. A steerable drill generally consists of two mechanical transmission components, an outer part providing steerability and an inner part transmitting drilling torques. Existing works on steerable drill development mostly relied on compliant transmission approaches (i.e., continuum manipulators (CMs) [6], [7] and flexible shafts, also called torque coils [6], [7], [10]). CMs can work seamlessly with flexible shafts since the inner flexible shafts can conform smoothly and passively inside the hollow CMs. Those continuum steerable drills were shown to be...
sufficient for boring bone tunnels. However, due to their inherent compliance and underactuation, there was always a design trade-off between stiffness and dexterity [11], which made them unsuitable for precise and stable hard-bone work in confined anatomical spaces. This situation will be even exacerbated when the diameters of the instruments get smaller. In an attempt to address this issue, [10] proposed to use multiple rigid link segments and tendon-driven articulated joints to provide steerability while using a flexible shaft to transmit drilling torques. Unfortunately, the instrument was still large in size (Ø8 mm), and the flexible shaft prevented these articulated joints from offering their full dexterity, since it cannot bend sharply.

The goal of this work is to develop a robotic steerable surgical drill offering high stiffness, strength, and dexterity, simultaneously. We propose a solution using non-flexible transmissions, i.e., rigid links, articulated joints, and universal joints, instead of flexible CMs and flexible shafts. To evaluate the basic mechanical performance of the proposed drill, we integrated it with a customized actuation platform. To further demonstrate the concept and feasibility of robotic steerable drilling in confined space in MISF, we developed an instrument integrated it with a customized actuation platform. To further demonstrate the concept and feasibility of robotic steerable drilling in confined space in MISF, we developed an instrument compatible with the da Vinci Research Kit (dVRK) [12], and integrated it with the patient side manipulator (PSM) of the dVRK. In sum, the main contribution of this work lies in the following aspects:

- Development of a Ø6.4-mm 2-degree-of-freedom (DoF) tendon-driven articulated surgical drill for MISF (Section II). Each modular joint of the drill consists of a high-strength hollow geared rolling joint and an inner high-speed drilling torque transmission mechanism. This joint module allows for an abrupt bend (±45°) in a tight space. The non-flexible nature of this drill offers high stiffness and high dexterity, simultaneously, which are hardly achieved by its flexible counterparts. To the best of our knowledge, this is the first fully non-flexible steerable surgical drill for preparing screw holes in bone.

- Proposal of an end-to-end model-free learning-based approach for estimating joint angles from measured motor angles using Recurrent Neural Network (RNN). This method significantly simplifies the accurate modeling and calibration process for manufacturing errors and hysteretic behavior of the proposed tendon-driven wrist (Section III).

- Experimental validation of the developed articulated drill, including: 1) kinematic accuracy, strength, and stiffness tests on a customized actuation platform; 2) drilling performance test and feasibility study of robotic-assisted steerable drilling through a slender tubular retractor, mimicking a hole-drilling scenario in MISF (Section IV).

II. MECHANICAL DESIGN AND ANALYSIS

The key contribution of the proposed drill design lies in its tip at the distal end, which consists of a drill bit, a drill bit collet, and a 2-DoF articulated drilling wrist. We integrate the drill tip with a stainless steel tube shaft and a
dVRK-compatible instrument backend into an exchangeable instrument of the PSM of the dVRK. In this section, we first calculate the required drilling force and torque based on literature results and then present the design and analysis of each mechanical component.

A. Requirements of Drilling Force and Torque

As an initial attempt, we adopt the existing result from [13] to estimate the required force \( F_d \) (N) and torque \( T_d \) (mNm) for bone drilling.

\[
F_d = 2.5\sigma_U(f/\omega)D\sin(\theta/2), \quad T_d = 0.625\sigma_U(f/\omega)^2D^2, \quad (1)
\]

where \( \sigma_U \), \( f \), \( \omega \), \( D \), and \( \theta \) are the ultimate tensile stress of bone (MPa) and the feed rate (mm/min), spindle speed (RPM), outer diameter (mm), and tip angle (°) of a drill bit, respectively. We use the following parameters, \( (\sigma_U, f, \omega, D, \theta) = (150, 30, 2000, 2.4, 118) \), which are reasonable for orthopaedic procedures according to [5], to estimate the required force and torque, which gives \( F_d \approx 3.6 \) N and \( T_d \approx 8.1 \) mNm.

B. Two-DoF Tendon Driven Articulated Drilling Wrist

The 2-DoF wrist is made up of 2 modular tendon-driven articulated joints with inner torque transmission mechanisms.

1) Geared Rolling Joint with a Large Inner Lumen: Geared rolling joints have proven structurally strong and able to rotate a large angle [14], [15]. Moreover, the length changes of one pair of tendons driving a properly designed rolling joint are theoretically negative to each other [14]. This allows using one motor to drive one joint without designing any extra nonlinearity compensation mechanism for driving the tendons. However, those joint designs cannot be readily used for our articulated surgical drill application, which requires a miniaturized dimension and a large inner lumen for drilling torque transmission.

We propose a new Ø6.4-mm geared rolling joint design with a Ø2.5-mm inner lumen to contain an inner torque

Fig. 2. Design of a tendon-driven geared rolling joint with a large inner lumen. (a)-(b) Joint assembly and its exploded view. (c)-(e) Side views of the proposed joint at different joint angles.
transmission mechanism (Fig. 2 (a) and (b)), which is tailored for our articulated drill application. This joint is composed of 2 pairs of gears, rolling against each other at the 2 sides of the central channels, and two dumbbell-shaped links, connecting the centers of the gears (see Fig. 2 (a) and (b)). The gears not only serve to make the two joint bases roll against each other (Fig. 2 (c)-(e)), but also prevent the torsional motion of the joint. Moreover, the two dumbbell links are used to support axial forces and prevent gears from disengaging from each other. Finally, one pair of notched elastic rings are used to stop the dumbbell links from moving out of the holes on the joint bases, which are glued or welded onto the joint bases after preliminary evaluation.

To ensure the strength of our joint design, we conducted a comprehensive finite element analysis (FEA) using Abaqus FEA 2019 (see Fig. 3). After multiple design iterations, we finalized the joint design shown in Fig. 2 (a)-(b). FEA results showed each dumbbell link can support over 15 N axial forces while each pair of gears can bear more than 10 N force, with the maximum stress below the yield stress of the materials (i.e., 200 MPa for SUS304 stainless steel). The maximum stresses of the dumbbell links appear to be tensile stresses at the stretched sides due to the bend. Meanwhile, the maximum stress of the gear teeth is at tooth roots.

2) High-Speed Drilling Torque Transmission Mechanism: A universal joint (see Fig. 4 (a)) is used inside each rolling joint to transmit torques for drilling. It consists of an input shaft, an output shaft, and a cross shaft connecting the input and output shafts. The cross shaft is made up of one cube with two perpendicular intersecting through holes and four small shafts, which connect each other via interference fit and glue bond, as shown in Fig. 4 (b). Contrary to the flexible shafts used in [6], [7], [8], [10], which have minimum bend radii, universal joint allows for a much sharper bend (In our experiment, we verified the universal joint functioned properly as long as the joint angle was within ±45°). For illustration, a complete joint module assembly is shown in Fig. 4 (c).

FEA was conducted for the universal joint (see Fig. 5). The results showed our proposed universal joint design can support more than 16 mNm torque transmission when the input and output shafts are co-linear (8 mNm for each side). It is expected that, as the bend angle increases, the torque transmission capability will decrease.

3) Drill Tip Assembly: By combining 2 of the proposed joint modules with their rotational axes perpendicular to each other, we obtain a 2-DoF articulated drilling wrist (see Fig. 6 (a)). Interlocking mechanical features are used on each pair of connected shafts to transmit torques from the proximal backend motor shaft to the distal drill bit collet. To achieve higher dexterity, we can combine more of those joint modules.

Fig. 4 shows the cross-section view of the drill bit and its collet. The drill bit collet with a ø2.4-mm lumen allows for exchangeable drill bits for different purposes, such as burrs, cutters, debinders, and screwdrivers. A nut (yellow) confines the drill bit collet along the axial direction. Two notches are
cut at the two sides of the drill bit collet to make the drill bit collet bendable (see Fig. 6 (c)). By tightening the drill bit collet nut (pink), which has a conic lumen, we can squeeze the drill bit collet and fix the drill bit onto the drill bit collet.

C. dVRK-Compatible Instrument Backend

Fig. 7 (b) shows the backend mechanical design of the proposed articulated drill instrument. 3 capstans were used on this backend: M1 (actuating Tendon 1 and 3 in Fig. 9) and M2 (actuating Tendon 2 and 4) were for driving the 2 joints at the wrist while M3 was for rotating the instrument shaft. A brushless DC (BLDC) motor (F40 Pro II from T-MOTOR Inc.) was used to drive the distal-end drill bit through a Ø2.5-mm long shaft and two universal joints. A 14-bit magnetic encoder (AS5047D from AMS Inc.) was installed at the end of the instrument to measure the angular position of the motor rotor that was connected to a round magnet. The angular position was then used for commutation and speed control.

D. Physical Hardware of the Developed Articulated Drill

The initial prototype of the proposed articulated drill is shown in Fig. 8. The drill tip was made of SUS304 through CNC machining. the long shaft tube is an off-the-shelf SUS304 tube, which was machined at its two ends to connect the drill tip and backend. The capstans, driving plates, bearings, and capstans on the backend were all standard components adopted from dVRK instruments while other parts were customized through either CNC machining or 3D printing. \( \varnothing 0.5\) mm tungsten tendons \((7 \times 7 + 8(1 \times 19)\) from Fort Wayne Metal Inc., USA) were used to transmit motion from backend capstans to distal-end joints. 2 N pre-tensioning force was applied to each tendon to minimize backlash and tendon slack.

III. RECURRENT-NEURAL-NETWORK-BASED MOTOR-JOINT KINEMATICS

Robotized tendon-driven surgical instruments are generally working in a semi-closed-loop control fashion (e.g., [12]), where motors are in fully closed-loop control while joint angles are controlled based on the analytical kinematics from motor space to joint space, called motor-joint kinematics. One drawback of this approach is that the analytical kinematics might be inaccurate due to manufacturing and assembly errors. The situation will get worse in miniaturized dimensions, where errors become more sensitive. A common remedy for this problem is model-based error modeling followed by a systematic calibration, which requires a large amount of system-specific parameter tuning and troubleshooting. Furthermore, the hysteretic effect from tendon-pulley systems is generally hard to model and identify. In this section, we propose to use an end-to-end model-free learning-based approach to estimate joint angles from motor angle histories using an RNN. We start with a model-based motor-joint relation in an analytical form, which serves as a baseline in our experiments. Next, we introduce our RNN-based approach.

A. Model-Based Motor-Joint Kinematics

Fig. 9 shows the geometric diagram of the 1st joint of the wrist and also indicates the locations of tendons, where 
\[ I_1 = \left[ l_1^1 \ l_1^2 \ l_1^3 \ l_1^4 \right]^T \in \mathbb{R}^4 \] is the lengths of the tendons passing...
though this joint. The 2nd joint is perpendicular to the 1st one with the same design. According the modeling approach for this type of tendon-driven rolling joint [14], the tendon length changes through the 1st and 2nd joints are given by $\delta l_1, \delta l_2 \in \mathbb{R}^4$, respectively, as shown in (2). The whole tendon length changes $\delta l \in \mathbb{R}^4$ can be achieved by the sum of $\delta l_1$ and $\delta l_2$. Meanwhile, the linear relation between motor angles $\theta_m \in \mathbb{R}^2$ and $\delta l$ can also be easily built, with the knowledge of the radius of the capstans driving the 4 tendons, $r_c = 2.75$ mm, which are installed on the 2 motor shafts.

$$\delta l = 2r_{ct} \sin \frac{\theta_1}{2} \begin{bmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \end{bmatrix} + 2r_{ct} \sin \frac{\theta_2}{2} \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \theta_m,$$

where $r_{ct} = 1.556$ mm is the effective moment arm of the tendons. It can be easily seen that, in (2), the first 2 rows are negative to the last 2 rows. Using this property, we can further simplify this equation and derive the motor-joint kinematics as

$$\theta_m = \frac{2r_{ct}}{r_c} \begin{bmatrix} \sin \frac{\theta_1}{2} + \sin \frac{\theta_2}{2} \\ -\sin \frac{\theta_1}{2} + \sin \frac{\theta_2}{2} \end{bmatrix}.$$  

(3)

**B. RNN-Based Motor-Joint Kinematics**

The model-based approach in (3) is subjected to modeling errors and tendon-pulley hysteresis. To improve accuracy, we apply Long Short Term Memory (LSTM) [16], an efficient and popular RNN, to model the mapping from historical motor angles to joint angles. Here, the LSTM can be represented as

$$i_t = \sigma(W_i \theta_{m,t} + U_i h_{t-1})$$

$$f_t = \sigma(W_f \theta_{m,t} + U_f h_{t-1})$$

$$o_t = \sigma(W_o \theta_{m,t} + U_o h_{t-1})$$

$$c_t = \phi(W_c \theta_{m,t} + U_c h_{t-1})$$

$$h_t = o_t \odot c_{t-1} + i_t \odot \tilde{c}_t$$

$$\tilde{h}_t = W_{fc} h_t,$$

(4)

where $\theta_{m,t} \in \mathbb{R}^2$ is the motor angle vector at time $t$, $\sigma(\cdot)$, $\phi(\cdot)$, and $\odot$ denote the sigmoid function, hyperbolic tangent, and Hadamard product, respectively, $i_t$, $f_t$ and $o_t$ are input, forget and output gates, respectively, $\tilde{c}_t$, $c_t$, and $h_t$ are cell input activation vector, cell vector, and output vector, respectively. $W_i, W_f, W_o, W_c, U_i, U_f, U_o$ and $U_c$ are parameter matrices for the LSTM. The LSTM layer is followed by a fully connected layer, giving the estimation of joint angles at $t$,

$$\hat{\theta}_t = W_{fc} h_t,$$

(5)

where $W_{fc}$ is the parameter matrix for the fully connected layer. In this paper, we use 200 LSTM cells and set the length of the historical horizon to 100.

**IV. EXPERIMENTS AND RESULTS**

We first evaluated the basic mechanical performance of the distal end of the proposed articulated drill, including accuracy, strength, and stiffness, on a customized tendon actuation platform (Fig. 10 (a)). We then studied the system-level performance of the drill on the dVRK using our dVRK-compatible articulated drill instrument (Fig. 8 (a)).

Fig. 10. Experimental setups. (a) Customized tendon actuation platform. (b)-(c) Integrated robotic-assisted steerable drilling system based on the dVRK with our proposed articulated drill instrument. (d) Simulated bone phantom with an F/T sensor measuring drilling forces.

**A. Experimental Setups**

1) Customized Tendon Actuation Platform: As shown in Fig. 10 (a), the customized tendon actuation platform has 2 BLDC motors (3242BX4, Faulhaber Group) driving tendons and 1 BLDC motor (EC-4pole 22, Maxon Precision Motors) spinning the drill shaft. All these motors were driven by motor drivers (G-MOLTW16/100EOT) from Elmo Motion Control. We used an industrial PC running Simulink Real-Time to communicate with the motor drivers at 2 kHz via EtherCAT. Compared to the dVRK, which was primarily designed for soft-tissue laparoscopic surgery, our customized actuation platform was particularly designed to evaluate high-performance instruments with high precision and stiffness.

2) dVRK-Based Robotic Steerable Drilling System: We integrated the articulated drill instrument (Fig. 8 (a)) with the PSM of the dVRK (Fig. 10 (b)-(c)). The integrated system was programmed (or teleoperated) to follow specific trajectories to evaluate its drilling capability. A customized $\Theta 2.4$ mm drill bit was attached to the drill collet for drilling holes. High-level control software for the PSMs and the master tool manipulators (MTMs) ran on a PC under Linux and the Robot Operating System (ROS) [17]. The VESC$^1$, an open-source BLDC motor controller, controlled the BLDC motor to spin the drill shaft at the instrument backend. During teleoperation, gravity compensation [18] was enabled for the MTMs.

**B. Training and Test of the RNN for Motor-Joint Kinematics**

1) Data Collection: 1000 via points were iteratively generated in joint space $\theta$, starting from $\theta^1 = (0,0)$. A subsequent

---

1https://vesc-project.com/
As compared to the model-based method in (3), the LSTM network decreased the RMSEs by (50.0%, 62.9%). In each approach, the RMSE of $\theta_2$ was slightly larger than that of $\theta_1$ because tendons first passed through Joint 1 to actuate Joint 2, which resulted in more motion loss in Joint 2. As shown in Fig. 11 (b), the LSTM-predicted joint angles were closer to the measured joint angles than the model-predicted ones. In particular, at turning points, with the incorporation of historical information, the LSTM network also accurately predicted the joint angles while the model-based approach failed to do so. This result indicates the trained RNN achieved strong generalization of the nonlinear tendon-coupled kinematics and hysteresis of the proposed drill wrist.

According to the theoretical analysis in [21], the accuracy requirements for spinal pedicle screw placement vary between vertebrae. For lumbar spine, the maximum translational and rotational errors are 0.65, 0.85, 1.5, 3, and 3.8 mm and 2°, 2.7°, 4.9°, 9.8°, and 12°, respectively, from L1 to L5. From a statistics perspective, our steerable drill largely meets the accuracy requirements for L3 to L5. It should be sufficient for the real surgical usage as, during surgical operations, surgeons normally use additional intraoperative imaging techniques, such as endoscope and Computed Tomography (CT), to fine-tune the pose of the drill before drilling.

### C. Strength Test

The mechanical strength of the proposed drill was tested in the lateral and axial directions. Since the direct-drive motors on the customized actuation platform were not able to provide enough torques for those extreme cases, we clamped the tendons to provide sufficient forces on the tendons. In the lateral strength test (see Fig. 12 (a)), a 500 g weight was hung on the horizontally placed drill bit when $\theta = 0$. This shows the developed articulated drill can support more than 5 N lateral forces without being broken. In the axial strength test (see Fig. 12 (b)), we pushed the drill against a weight scale, and it showed the drill can hold over 19 N axial forces without buckling and breakage. This experiment verified that the mechanical strength of our drill can satisfy the force requirements for bone drilling (see Section II-A).

### D. Drill Stiffness Test

The stiffness of the developed articulated drill was tested in the lateral (x- and y-axis) and axial (z-axis) directions of the drill bit (Fig. 10 (a)) at $\theta = 0$. A high-precision (0.01 mm resolution) manual 3-axis linear stage was used to push...
the drill bit tip along different directions while an F/T sensor (Nano 17 from ATI-IA Inc.) measured the interaction forces. The force-displacement relations are shown in Fig. 14. The slopes of the linear approximations (i.e., the stiffnesses of the drill) were about 2.4, 5.4, and 67.2 N/mm along the x-, y-, and z-axis, respectively. The measured stiffness along the x-axis is lower than that along the y-axis partially because the moment arm for the 1st joint was longer than that for the 2nd joint when a force was applied at the tip of the drill bit. Moreover, as shown in Fig. 10 (a), the articulated drill was attached to a long thin plate, similar to a long thin beam, which had a much higher area moment of inertia and thus stiffness about x-axis than about y-axis. The measured stiffness along the z-axis was much higher than those along the x- and y-axis because the deformation of the stainless steel parts of the drill was negligible within its yield strength. During a hole-drilling process, drills generally require large forces along lateral directions to keep drilling directions. The high stiffness of our drill ensures high stability for precise drilling, which is hardly achieved by its flexible counterparts.

**E. Drilling Test into Simulated Bones**

To evaluate the bone drilling capability, we performed a drilling test into simulated bone materials (Block, Solid Foam, 15 PCF from SawBone Inc., US) with the drill instrument installed on the PSM under a constant feed rate of 1 mm/s while the drill bit was spinning at 1000 RPM. During the test, we set $\theta_1 = 0^\circ$ while we varied $\theta_2$ as follows, $\theta_2 = 0^\circ$, $15^\circ$, $30^\circ$, and $45^\circ$. We recorded the interaction forces between the drill and the bone using an F/T sensor (see Fig. 10 (d)). After drilling, we measured the diameter of each hole using a digital microscope (ZY-H500C from Zongyuan Inc., China).

Fig. 13 shows the measured forces. When $\theta_2 = 0^\circ$, the mean force in the z-axis increased approximately linearly from about 1 s to 3.5 s, as the drill bit fed at a constant speed. From about 3.5 s to 5.5 s, the force stayed relatively stable, as the drill bit consistently removed the bone materials while feeding. From about 5.5 s to 8.5 s, the drill bit retreated at a constant speed, causing the measured force to decrease approximately linearly. Across different joint angles, the axial forces exhibited a consistent pattern. The lateral disturbances (the forces in the x- and y-axis) were kept to a minimum ($F_x, F_y \approx 0 \pm 0.3$ N) even at different joint angles, demonstrating the high structural stability of the proposed drill. The actual diameters of the holes drilled with a $\varnothing2.4$-mm drill bit using our drill are from $\varnothing2.46$ mm to $\varnothing2.56$ mm with high consistency, as shown in Fig. 15. As a reference, we also drilled a hole ($\varnothing2.41$ mm) using
a bench drilling machine. This can be regarded as the ideal drilling scenario, where the drill shaft was highly rigid and stiff and the feeding of the drill bit had negligible kinematic errors. Compared to this hole, the holes drilled using our robotic steerable drilling system were just slightly larger and within the acceptable tolerance of medical screw holes.

**F. Steerable Drilling Test via a Slender Tubular Retractor**

To demonstrate the capability of drilling in confined space, we conducted a steerable drilling test, where a user was required to teleoperate our device to drill a hole in a tight space at an acute angle (Fig. 16). The setup consisted of a 3D-printed slender tubular retractor and a piece of simulated bone at an acute angle (Fig. 16). The setup mimicked the hole drilling process into the spine during spine fusion surgery. During this test, we programmed the PSM to move the instrument through the retractor to reach the target site (Fig. 16 (b)). Once the drill tip reached the target site, the user teleoperated the instrument to drill a hole into the simulated bone (Fig. 16 (c)-(d)) and retreat when the drilling finished (Fig. 16 (e)). When the drill tip was around the target site, the drill shaft was mostly constrained inside the slender retractor. From our experimental result, our device still showed sufficient dexterity to adjust the drilling orientation, which can hardly be done by a straight-shaft drill.

**V. CONCLUSION AND FUTURE WORK**

We developed a miniaturized tendon-driven articulated surgical drill, which was designed to be inherently strong and stiff to deal with hard bony tissues in confined space. Experimental results showed high stiffness and strength of the proposed drill. On a customized actuation platform, the proposed drill showed high accuracy (RMSES $\leq 0.85^\circ$) for estimating joint angles from motor angles through an RNN-based approach. We also integrated our instrument with the dVRK system and experimentally verified that the integrated drilling system can provide high drilling stability and significantly enhance distal dexterity for hole drilling in confined space in MISF.

In the future, we will integrate our instrument with a robotic arm that processes higher precision and stiffness necessary for orthopedic surgery and also use it to conduct a cadaveric study to evaluate the usability and effectiveness of the proposed instrument in a clinically relevant environment. Besides preparing screw holes for spine fusion, we will also explore the potential of the proposed device in minimally invasive spine decompression.

**REFERENCES**